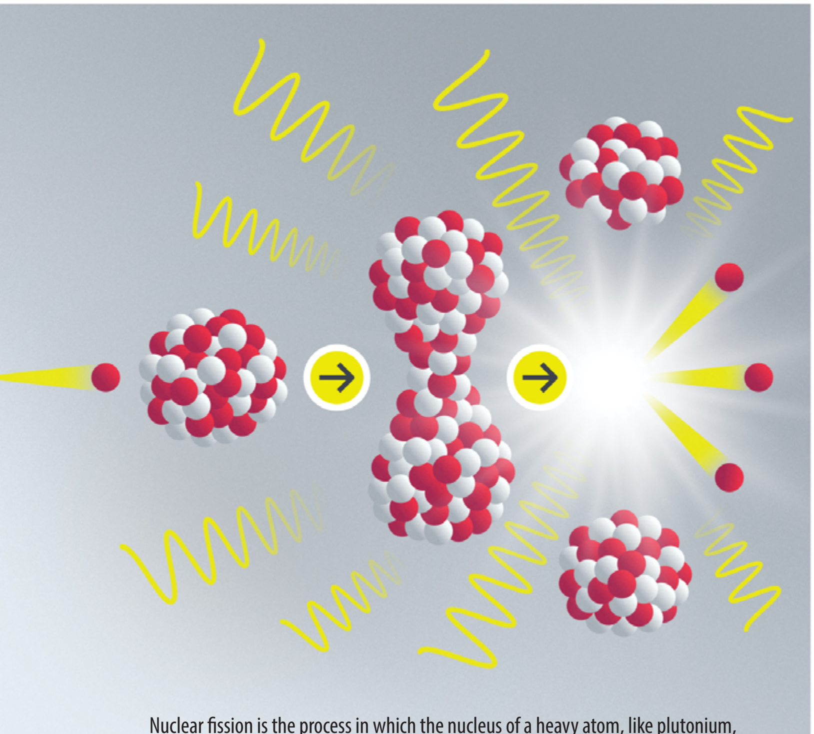
The bomb without the boom

A new subcritical measurement tool will help scientists protect and preserve the nation's stockpile.

TWENTY-FIVE YEARS AGO LAST MONTH, DEEP UNDERGROUND in the remote Nevada desert, the United States conducted its last full-scale test of a nuclear weapon. That test, led by Los Alamos National Laboratory, was code-named "Divider" and, though not known at the time, would serendipitously come to represent a divide between two eras of nuclear-weapons science. With the cessation in the 1990s of underground nuclear explosions, nuclear-weapons science was forced in a new direction. Grounded now in computer simulation, modern nuclear-weapons science has produced groundbreaking new discoveries essential to national and global security.

In addition to ceasing full-scale testing, the United States has been reducing the size of its arsenal, which is down by more than 90 percent since its peak in the 1960s. How to maintain the nuclear deterrent and look after the stockpile as it ages is one of the national security challenges with which Los Alamos National Laboratory has been charged. This challenge, in the absence of nuclear testing, necessitated a paradigm flip: instead of from the top down, scientists began to study nuclear weapons from the bottom up. Rather than seeking to understand the parts by studying the whole, inferring that if the whole functions as expected, then each part must have worked as predicted, designers began to operate from the other direction—by seeking to understand each and every piece and part, to be able to infer the function of the whole.

Science-based stockpile stewardship, as this process has come to be called, is how scientists at Los Alamos and other national labs ensure that nuclear weapons remain safe, secure, and reliable. The change from top-down to bottom-up science has helped shape the Laboratory's evolution. Initial computer simulations were insufficient to accurately model the details of a nuclear explosion, so new codes had to be written. The new codes required more computing power than existed, so new computers had to be built. The new computers needed higher-quality data for their simulations, so new types of experiments had to be invented. These three arenas of innovation—codes, computers, and experiments—allow scientists to ask and answer questions vital to maintaining our country's aging stockpile. And now a new type of experiment—one that can make measurements that haven't been made since the cessation of underground testing—is going to provide new insight into the conditions inside exploding nuclear weapons.



Nuclear fission is the process in which the nucleus of a heavy atom, like plutonium, absorbs an incident neutron (red) and consequently splits into (typically) two pieces, releasing more neutrons, gamma rays (yellow waves), and energy.

Peculiar plutonium

Los Alamos physicist Anemarie DeYoung was always enamored of the cleanness and purity of solving problems with exact formulae.

"Take the standard model of particle physics for example," she explains, "I think it's the purest, most beautiful theory in the universe. You can describe all the physics with just a few particles; it's really amazing."

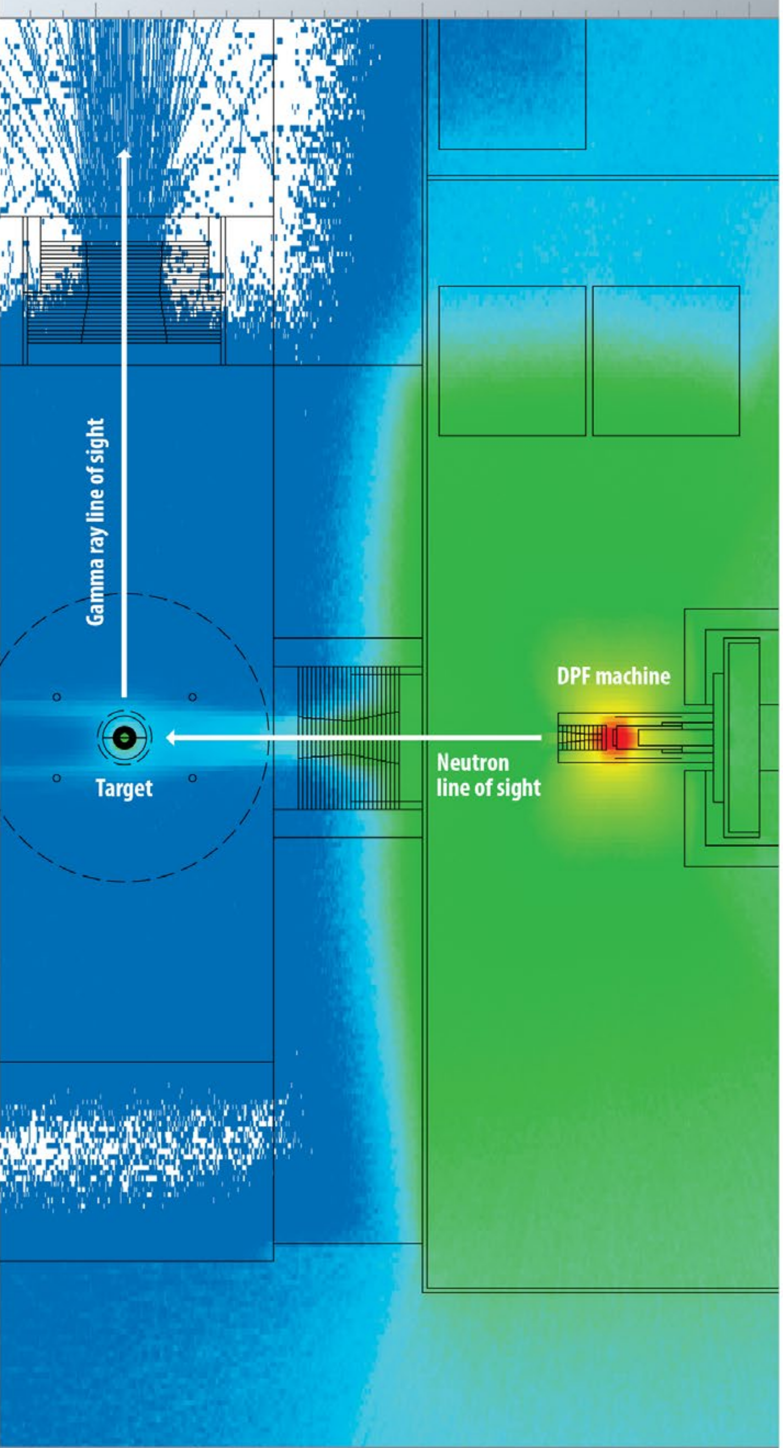
But DeYoung never imagined she would have weapons expertise listed on her resume; it was never her goal. She knew she would go into some field of physics, having had both early exposure—her father was a physicist—and positive scholastic mentors. But when a project came along that she found especially interesting and challenging—namely designing and building an experiment to study the implosion of plutonium—she jumped at the chance to lead it.

Science-based stockpile stewardship is how scientists ensure that nuclear weapons remain safe, secure, and reliable.

It's very, *very* difficult to model the details of a nuclear device. At the heart of the issue lies the enigmatic metal plutonium. Plutonium—an almost entirely manmade material—has a number of properties that make it difficult to work with: it expands and contracts more than most metals, it increases rather than decreases in density when it melts, it's not as magnetic as it ought to be, and it's radioactive. The weapons in the U.S. stockpile have pits of plutonium at their cores.

During the era of mass production, weapons were built with the assumption that they would be periodically replaced and updated. Today, a combination of limited production and life-extension programs has been established to keep the stockpile updated. Although the days of full-scale testing provided a lot of understanding, some of the details of oddball plutonium, especially its behavior inside a weapon, are still lacking. Over the past 25 years, through the bottom-up approach, many of the missing details have come together. But DeYoung and colleagues are finding that they need to be able to measure the nuclear reactivity of plutonium under conditions like those found inside a nuclear explosion, a measurement that has been unavailable since the cessation of testing.

To give them better insight into plutonium's behavior, scientists study one of its most unique capabilities: fission. Fission is the process in which the nucleus of a heavy atom, like plutonium, absorbs an additional neutron and subsequently splits into pieces (typically two), releasing more neutrons, gamma radiation, and of course energy. The neutrons released can then be absorbed by other nuclei, causing them, too, to break apart and release even more



Simulation setup of neutron-diagnosed subcritical experiment (NDSE). Laboratory supercomputers running the Monte Carlo N-Particle transport code were used to simulate trillions of neutrons, one at a time, traveling from the dense plasma focus (DPF) machine to the target, as well as all of the resulting particles and their flight paths. Neutrons travel from the DPF machine through a tunnel and then collide with the target object. Gamma rays (and neutrons) leave the object in all directions at once, with some traveling down a second tunnel toward the gamma-ray detectors (not shown).

neutrons in a fission chain reaction. The denser the material is, the closer the nuclei are to one another, and the faster the chain reaction progresses.

Once a chain reaction is established, neutrons are both generated and lost from the system (neutrons can just travel out of the material rather than be absorbed by a nucleus). If the number of neutrons generated is exactly equal to the number lost, the system is described as critical. This is what occurs in nuclear-power reactors: control rods are used to absorb excess neutrons to maintain criticality while preventing a runaway chain reaction or, in an emergency, to quench the reaction. If the number of neutrons generated in a nuclear system exceeds the number lost, then the neutron population increases as a function of time and the system is called supercritical. Supercriticality is the condition underpinning the inside of a nuclear weapon, which results in a fast outburst of tremendous energy.

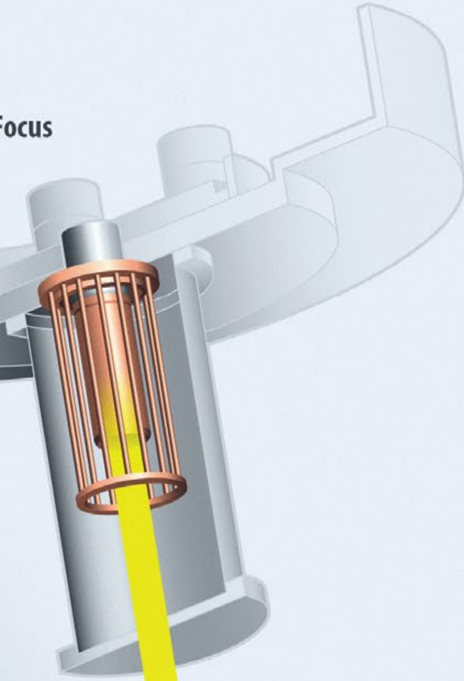
If, however, the neutron population *decreases* as a function of time—that is, more neutrons are lost than are generated—then a chain reaction will not, *can* not, be sustained. Although fission does occur, the chain reaction is dying as soon as it begins. This condition is called subcritical and it's where weapons testing lies today. DeYoung and her team are developing a new kind of fission measurement, called a neutron-diagnosed subcritical experiment (NDSE) that will restore their ability to study the fission behavior of plutonium under conditions like those found inside a nuclear explosion, but without the nuclear explosion.

Subcrits and hydrotests

"An NDSE is not a new idea," says DeYoung, "but it's an idea that has only recently reached maturity, due to related advances. Things like new neutron sources, better detector technologies, faster electronics, and improved supercomputer simulation capabilities have made this the perfect time to build it."

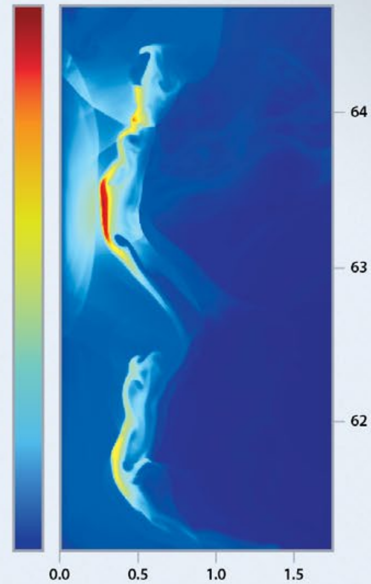
Subcritical experiments, or subcrits, to use the parlance of the field, are physical experiments that explore the dynamic behavior of fissile materials like plutonium. Subcriticality is achieved through careful design to ensure that neutron multiplication—the release of multiple neutrons by each nucleus undergoing fission—is always decreasing in rate, toward inevitable extinction. Because subcrits use the actual fissile materials that are used in weapons, and because they reach the physical conditions of the early parts of a nuclear explosion, the data that subcrits provide are directly relevant to the computer codes that support stockpile stewardship. Ongoing improvements in experimental diagnostics—such as a major new radiographic capability that is part of the same project as the NDSE (the Enhanced Capabilities for Subcritical Experiments project) and just as transformational—continue to increase the importance of subcrits for stockpile stewardship.

Hydrotests, another mainstay of stockpile-stewardship research, study the process of implosion, the triggering event for a nuclear weapon to go supercritical. ("Hydro" comes from the Greek word for water, and refers to the fact that the high

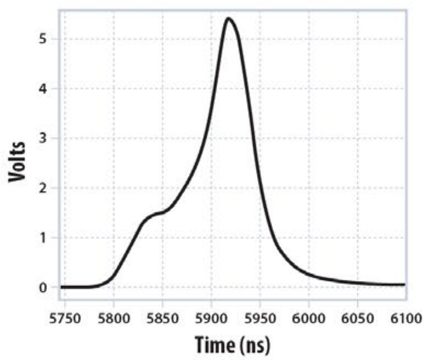


1 Dense Plasma Focus (DPF) machine

Detail of the DPF machine head showing the region inside the deuterium and tritium gas-filled chamber where the neutron pulse forms. The DPF machine was developed by National Security Technologies LLC, with modeling and simulation conducted by Los Alamos's Theoretical Division.



A simulation showing a typical neutron pulse forming within the DPF head. The color scale indicates deuterium-tritium density, the x-axis indicates radial position within the cylindrical chamber (with 0 at the center), and the y-axis indicates the length of the chamber (with 0 at the base). The model can recreate, and thus predict, how neutron pulses are formed in the DPF, allowing scientists to optimize the system.



A representative DPF neutron pulse showing that the machine produces sufficient neutrons (about a trillion) in a short enough period of time (about 100 nanoseconds) to be a good neutron source for the neutron-diagnosed subcritical experiment.

2 Target object

The object under study, whether fabricated from boron, highly enriched uranium, or plutonium, is located in the direct line of sight of both the DPF machine and the gamma-ray detectors, while these themselves are out of sight of one another. Neutrons from the DPF cause nuclei in the test object to fission and release additional neutrons and gamma rays in all directions, with some hitting the gamma-ray detectors.

pressures and temperatures generated inside an implosion cause some of the materials to behave like liquid). During a hydrotest, x-ray imaging and other diagnostic methods are used to study the symmetry and compression of an imploding

This will help scientists study plutonium under the conditions found inside a nuclear explosion—without the nuclear explosion.

pit-like target, usually made of some other heavy metal that shares certain properties of plutonium.

An NDSE is very particular kind of subcritical hydrotest that uses neutrons to probe the state of plutonium itself during an implosion. That's correct, it can use a real plutonium pit very similar to those inside of stockpile weapons. The NDSE's coupling of the implosion process with plutonium as a target and a direct measurement of neutron multiplication as the resultant data will be more like a real test than any of the experiments done since real testing ceased. The addition of neutron data from the subcritical implosion of a dynamic object would enable much of the data generated during the testing era to be tied together with data generated after the cessation of testing. It will help scientists continue to meet the challenge of using old test data to validate new simulations and models.

The NDSE setup is basically this: a dynamic device—either a pit or a pit-like target—is imploded by explosives and bombarded by neutrons from a controlled external source. A pulse of about a trillion neutrons causes a momentary fission chain reaction in the target, just like what occurs in the first instant of a detonation, but instead of exponentially increasing as in a detonation, the assembly is subcritical, so the chain reaction goes extinct. The ability to control and extend the time it takes to go extinct is one of the key achievements of the NDSE—the longer it takes, the more data can be collected and the better the process can be understood. Even still, it's all over in a fraction of a second.

By determining the rate at which neutrons are generated, absorbed, or lost, scientists can calculate how a nuclear weapon would perform if allowed to go supercritical. Every fission event releases an average of three neutrons and eight gamma rays. The gamma flux—how many gammas hit the vertical plane of the detector's face per unit time—is measured, and because gammas and neutrons are generated at the same time and in proportional quantities, the gamma flux reveals the neutron population.

Why count gammas when what they're really after is neutrons? Because gammas are the cleaner measurement. The detectors are sensitive to both neutrons and gammas, but gammas travel faster than neutrons (even the high-energy neutrons produced by fission), so the gammas arrive at the detectors first. Unlike gamma rays, which travel uniformly at the speed of light, neutrons travel at varying velocities, so they trickle in to the detectors while the gammas arrive mostly all at once. Also, as the neutrons exit the target, they scatter off of surfaces and bounce into nuclei in the air, and these antics occasionally produce secondary gamma rays, which could conceivably hit a detector. By placing the detectors a certain distance away from the target, in what's called time-of-flight separation, the initial round of direct fission gamma rays can be tidily collected just before the mess of neutrons and non-fission gammas that follow. From there it's relatively straightforward to calculate the neutron population. In this way, key performance characteristics can be determined in the absence of a full-scale nuclear test.

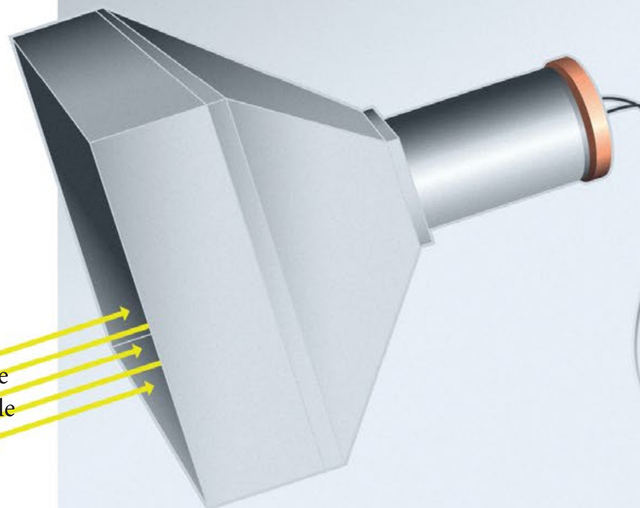
Everything but detonation

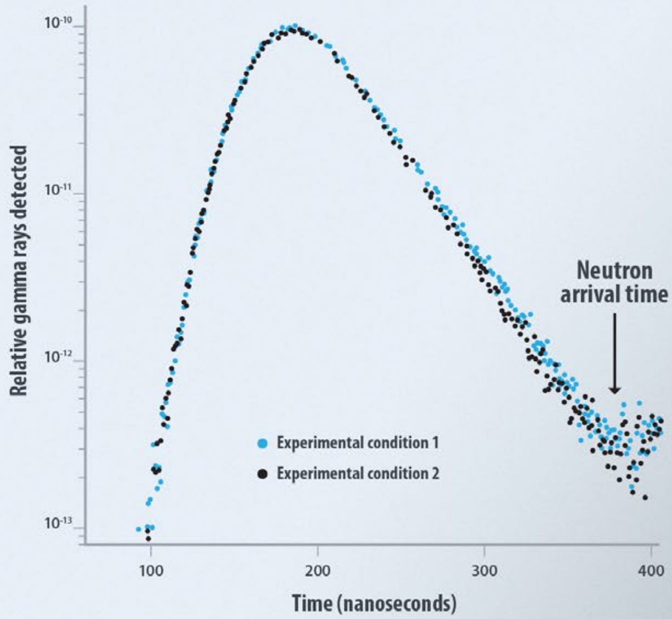
"This is more like a real full-scale test. It's as close as we've ever come," explains retired Los Alamos physicist and NDSE consultant George Morgan. "Since the cessation of testing we've been oriented toward understanding material properties rather than evaluating a whole device. This is, in fact, a real device, designed to stop just short of going supercritical. And the question is, 'how well did it function up to that point?'"

There are multiple challenges to developing an NDSE. One is getting enough neutrons in the initial pulse while ensuring comparatively few neutrons are generated thereafter; another is developing an experimental setup that provides gamma-ray detection with maximal signal and minimal noise. DeYoung's team, in collaboration with Department of Energy contractor National Security Technologies LLC (NSTec), has developed an improved neutron source, as well as improved gamma-ray detectors, and has successfully completed the proof-of-principle experiments. They started with a non-fissile static target (static meaning non-imploding) and are presently working with a fissile static target, inching with each iteration closer to the end-goal of fissile and dynamic—though always subcritical—plutonium.

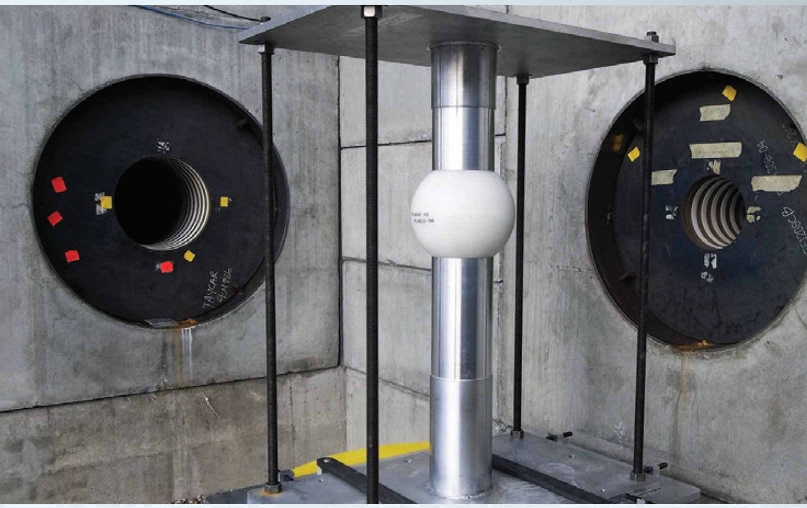
3 Gamma flux

The gamma-ray detectors use a liquid scintillator that absorbs the energy of incoming gamma rays, then re-emits that energy as light. The light signal gets converted to an electrical signal before being collected and stored on a computer.





Monte Carlo N-Particle simulations of gamma flux under two sets of experimental conditions help to determine optimal experimental settings. Gamma flux is a measurement of how many gamma rays hit the detector's vertical face per unit time. The rate of the gamma-flux decrease is known as gamma falloff and is given by the slope of the decline to the right of the peak: the steeper the slope, the faster the falloff. The gamma falloff is extremely sensitive to reactivity at this timescale, allowing scientists to adjust reactivity in the simulation for a high degree of control over the gamma falloff, which traces the rate of the subcritical chain-reaction decay. Because gamma rays travel faster and more uniformly than neutrons, the gamma-ray signal is used to calculate the neutron population.



The initial proof-of-principle work for the NDSE used a static (non-imploding), non-fissile target. Presently, researchers from the Laboratory's Nuclear Engineering and Nonproliferation and Physics divisions are experimenting with static but fissile highly enriched uranium in an above-ground laboratory at the Nevada National Security Site (NNSS). Here, a test object is positioned at the intersection of the line of sight of the dense plasma focus neutron pulse (tunnel on right) and the line of sight of the gamma-ray detectors (tunnel on left).

The next stage of the NDSE will be to measure a dynamic (imploding) and fissile plutonium target. This will require building the NDSE in the U1a underground facility at the NNSS. Comprising nearly a mile and a half of underground tunnels and alcoves, the U1a facility is a state-of-the-art laboratory dedicated to subcritical experiments and other physics experiments in support of science-based stockpile stewardship.
CREDIT: Nevada National Security Site

"We don't want to do everything that goes with using dynamic material until we know that our system is working as it should," says Morgan. "So we use a simple, safe, well-understood object to vet the system."

The isotope boron-10 is an ideal choice because it's non-fissile and static, but it has the convenient property that every time a nucleus captures a neutron, the nucleus emits a single gamma ray. Actually, when a boron-10 nucleus captures a neutron it emits an alpha particle (comprised of two protons and two neutrons) which leaves behind lithium-7. The lithium-7 is in an excited state, and when it relaxes to its ground state, it emits a gamma ray. So as scientists measure gamma emissions, they're basically watching boron-10 capture neutrons.

By shooting neutrons one at a time, the team created a time history of how gamma rays are emitted by the target. After that, the next step was to do a bunch of neutrons in one big pulse and see how well that matched the results from the piecemeal approach. If the results from both approaches matched, it meant the system was working. And DeYoung's system is working.

During the experiment, the gamma falloff—a data plot of the gamma flux—will show a single strong peak, one that increases then decreases rapidly to zero over several hundred nanoseconds. This measurement is important because the subcritical assembly produces about ten orders of magnitude fewer gammas than a nuclear test would, making it that much harder to get a reading, let alone a clean and precise one. The gamma falloff tells the scientists that the target is generating neutrons as predicted and that the neutron population is decaying as predicted, and it also reveals the accuracy and precision of the measurement itself. The actual measurements are compared to supercomputer simulation predictions to validate and fine-tune the simulation.

Previously, with the boron-10 target, and now with a static fissile target made with highly enriched uranium, the (now much larger) team is seeing good gamma falloff measurements that are similar in duration to what they predict—based on simulations—for plutonium. This is good news because it proves that the neutron source and electronics are working well, and that the simulations are good. Taken together, these conclusions suggest that the NDSE is indeed the long-desired innovative alternative to nuclear testing.

This is a real device, designed to stop just short of going supercritical. And the question is, how well did it function up to that point?

New innovations

One of the key advances enabling the NDSE is an improved neutron source, which is a modified version of an old design. A dense plasma focus (DPF) machine produces neutrons by heating and compressing a mixture of deuterium and tritium (both isotopes of hydrogen endowed with extra neutrons) to the point that the nuclei fuse, creating helium nuclei and freeing neutrons. The new version of the DPF was developed with help from the Laboratory's Theoretical Division, which used its modeling capabilities to simulate DPF neutron pulses. The simulations proved to be a powerful tool for characterizing the DPF and for working out some of the kinks in its performance. What makes this DPF unique is that it shoots more neutrons in a shorter time period than previous versions (approximately 10^{12} neutrons in 100 nanoseconds, compared to 10^{10} neutrons in 250 nanoseconds ten years ago), and it produces them in a more controllable way. With its bigger and faster neutron pulse, the DPF enables a longer-lasting and more uniform gamma falloff, demonstrating its suitability as a neutron source for the NDSE.

The gamma flux emitted from a fissioning system is a function of the system's reactivity, so in a subcritical system, this flux is small, and the detectors have to be quite sensitive. One approach for measuring the faint NDSE gamma flux is to use a liquid scintillator, which is a liquid medium that, when struck by an incoming particle of ionizing radiation (e.g., a gamma ray), absorbs the energy of the particle and re-emits the absorbed energy in the form of light. The team improved upon a well-known scintillator medium, making it faster and brighter than the conventional version, and called it Liquid VI. Each NDSE gamma-ray detector consists of a box containing a volume of Liquid VI, with a photomultiplier tube connected to the back to convert the light signal into an electrical signal, which can then be digitized and collected.

As the testing era recedes further into the past, making the most of the data from that bygone time requires tools like the NDSE.

Essential to the effectiveness of both the DPF and the gamma-ray detectors is the ability to create a tightly controlled line of sight with the object under study. The physical layout of the NDSE test facility involves multiple meters-long tunnels, down which the neutrons and gammas must fly. The setup had to be precisely modeled before it could be built because the team needed to be sure that enough neutrons from the DPF would reach the object and enough gammas from the object would reach the detectors.

Experts from the Laboratory's Physics Division first designed custom shielding and collimators to define the lines of sight and block interference so that the detectors could pick up a very small signal amidst a very large background. These, then, were optimized using simulations with the Monte Carlo N-Particle (MCNP) transport code developed by the Laboratory's Computational Physics Division. The MCNP simulations launched one neutron at a time and tracked with high precision everything that resulted—mostly neutrons and gammas. This was a critical step because it told the researchers whether, with the lines of sight they could create, they had any hope of making a good measurement with an actual experiment. The answer, obviously, was yes, and so the NDSE test facility was built.

The initial proof-of-principle experiments, a collaboration between Los Alamos and NSTec, were completed using the DPF neutron source and Liquid VI gamma-ray detector with the static boron target. The project is moving incrementally forward, now using static but fissile targets fabricated with highly enriched uranium to validate and improve the techniques. These experiments are being conducted at a dedicated above-ground facility at the Nevada National Security Site (NNSS). But for the NDSE to reach full maturity, it has to go underground.

Past but not passé

The end-goal of the NDSE is to probe a dynamic plutonium target. For safety and security reasons, this necessitates a move to an underground facility. Well, not a move exactly—the above-ground facility will stay put, but the team will build another one underground. All subcritical testing is done at the U1a facility at the NNSS. Built in the final years of the full-scale testing era, this underground facility was brand new when the cessation of nuclear testing nearly made it obsolete. It has since been repurposed into a highly sophisticated and specialized laboratory that meets all of the infrastructural, regulatory, and safety criteria needed for subcrits.

As the full-scale testing era recedes further and further into the past, making the most of the data from that bygone time becomes more and more crucial. Stockpile stewardship tools like the NDSE help advance scientists' abilities to ensure that nuclear weapons remain safe, secure, and reliable. The NDSE in particular holds the promise to restore access to the kind of data that has been out of reach since the days of testing.

The attrition of older employees from the Lab, people who actually worked on full-scale tests, poses the problem of knowledge transfer to today's scientists. The remedy, such as it is, is to fill in the gaps between decades-old test data and present-day simulation predictions with new data from subcritical experiments like the NDSE.

"Ideally we could just model," says DeYoung, "but we've found that we actually still have to measure too. So we need the right tools for that. To me, it's a no-brainer; I believe we absolutely need this tool, and the sooner the better." LDRD

—*Eleanor Hutterer*

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